Pergamon

0042-6989(94)E0083-W

Vision Res. Vol. 35, No. 1, pp. 1–6, 1995

0042-6989/95 $7.00 + 0.00

Interocular Transfer of Receptive Field Expansion in Cat Visual Cortex

ELIANE VOLCHAN,* CHARLES D. GILBERT†

Received 23 December 1993; in revised form 11 April 1994

Receptive fields in primary visual cortex have been shown to be capable of rapid expansion and contraction when exposed to an artificial scotoma, a masked segment of the visual field. To distinguish cortical from thalamic contributions to receptive field mutability, we tested interocular transfer of the effect in binocular cortical receptive fields, presenting the conditioning stimulus to the field in one eye and measuring size changes in the receptive field of the other eye. The expansion of the receptive fields in the non-conditioned eye was comparable to that in the conditioned eye. This result suggests that the expansion is due to mechanisms intrinsic to the cortex.

Cortical plasticity Contextual influences Primary visual cortex Artificial scotoma Receptive field expansion

A new view of the receptive field has emerged, one whose response specificity is influenced by the context within which a feature is placed and is dynamically altered by sensory experience. Manipulating visual experience can, over a period of months, induce large changes in cortical topography (Gilbert & Wiesel, 1990, 1992; Heinen & Skavenski, 1991; Kaas, Krubitzer, Chino, Langston, Polley & Blair, 1990), and, within minutes after making retinal lesions, produce a substantial increase in receptive field size (Gilbert & Wiesel, 1992; Chino, Kaas, Smith, Langston & Cheng, 1992). The short time-course of the effect led us to mimic the effect of retinal lesions by an artificial scotoma, a masked out region of the visual field including and surrounding the receptive field, outside of which the system is stimulated by an array of visual stimuli. After a period of conditioning extending for just a few minutes, the receptive field was induced to expand in area several-fold (Pettet & Gilbert, 1992). This effect could be reversed by stimulating the receptive field center, causing it to return to its original dimensions.

In attempting to determine the mechanism responsible for the receptive field expansion, we wished to determine at which stage in the visual pathway the reorganization occurs. Since cells in the lateral geniculate nucleus are monocular, any changes occurring at that stage would be expected to affect receptive fields in the eye receiving the conditioning stimulus, leaving the field in the other eye normal. We therefore attempted to explore whether there was interocular transfer of the expansion, when the artificial scotoma is shown to one eye and the receptive field size measured in the opposite eye.

METHODS

We recorded from 12 isolated single cells and four multiple units in area 17 of seven adult cats. Recordings were made in anesthetized, paralyzed animals with insulated tungsten microelectrodes and were restricted to the superficial layers of the cortex.

Anesthesia was induced initially by ketamine (10 mg/kg, i.m.), followed by sodium pentothal (20 mg/kg, i.v.). The EKG, EEG, temperature and expired CO_2 concentrations were monitored. The animal was intubated via tracheotomy, paralyzed with succinylcholine (10 mg/kg/hr) and artificially respired. Anesthesia was maintained with sodium pentothal (1–3 mg/kg/hr) and controlled by the presence of a slow-wave pattern in the EEG. The pupils were dilated with atropine and the nictitating membranes retracted with phenylephrine. Appropriate contact lenses were applied in order to focus the eyes on a tangent screen 1.5 m from the animal. The areae centrales were back projected on the screen. After making a craniotomy and resecting the dura, electrophysiological recordings were made with tungsten electrodes.

Receptive fields were mapped with hand-held projectors. In some cases, the extent of the receptive fields were established by automatic stimulation. Stimuli were present on a screen under computer control while the cell's spike times were acquired and stored on a second computer. Such stimuli usually consisted of small bars presented in the cell's preferred orientation. The bars were presented at 11 different positions evenly

*Department of Neurobiology, Institution Biofisica Carlos Chagas Fo., UFRJ, Rio de Janeiro, Brazil.

†To whom all correspondence should be addressed at: The Rockefeller University, 1230 York Avenue, New York, NY 10021-6399, U.S.A.

spaced along the orientation axis and each trial consisted of excursions of the bar in both directions, with a sawtooth movement of the bars. The total area covered by the test bars was several times the diameter of the original receptive field (see Pettet & Gilbert, 1992, Fig. 1). Measurement of receptive field size with a hand-held projector and with the quantitative technique described above was done before, during and after conditioning. After measuring receptive field size in the non-conditioned eye, the receptive field was measured in the conditioned eye. The magnitude of the response at each bar position is the integrated response histogram for the excursion of the bar, averaged over 10 trials, and expressed as a mean $\pm$ SD.

The conditioning stimulus consisted of a two-dimensional array of randomly placed oriented bars, each approximating the length of the receptive field under study. The orientation of the bars matched that of the receptive field, and were moved coherently in a direction perpendicular to the orientation axis. The field of moving lines covered an area 12 $\times$ 15 deg. A portion of the stimulated region was masked (occluded), and the occluder was placed such that the receptive field of the recorded cell lay in its center, and the diameter of the mask was roughly 3 times that of the receptive field. Initially the background stimulus did not activate the cell or increase the level of spontaneous activity, but over the period of conditioning the resting discharge of the cell often increased.

Binocular cells were selected for this study [including groups 3, 4 and 5 of the Hubel and Wiesel (1962) classification scheme]. For each cell the receptive fields

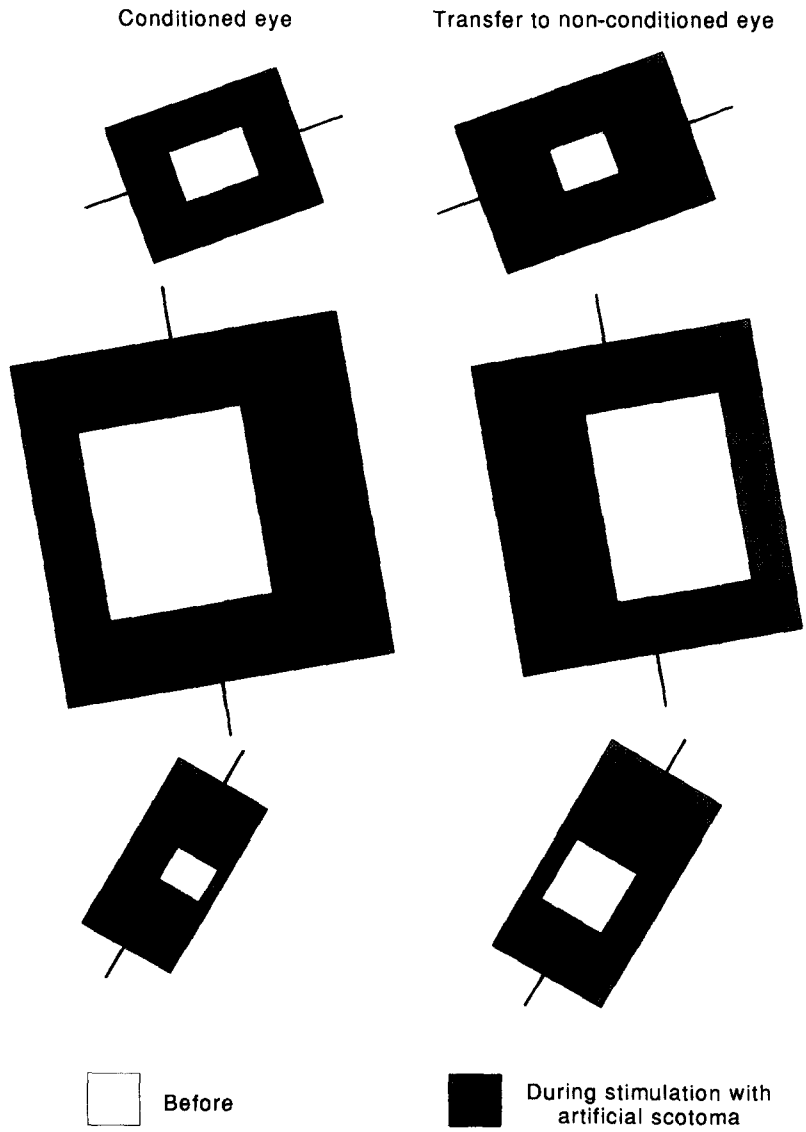

FIGURE 1. Examples of receptive fields of three cells measured by hand-mapping before (open rectangles) and during (shaded rectangles) conditioning with an artificial scotoma in the eye receiving conditioning and in the non-conditioned eye. The artificial scotoma consisted of a field of oriented bars moving back and forth in a direction orthogonal to their orientation. The orientation was chosen to match that of the receptive field. Within the stimulus a region of visual field was occluded. The size of the occluder was chosen to be roughly 3 times the diameter of the original receptive field. The occluder was positioned so that the receptive field was centered within it. All the cells included in the study were superficial layer complex cells in cat area 17.

of the two eyes were mapped separately. One eye was chosen for conditioning (C) with the artificial scotoma while the other, non-conditioned eye (non-C) was occluded so it could be used for testing interocular transfer of receptive field expansion. After monocular conditioning for approx. 10 min the conditioned eye was occluded and the other occluder was removed from the non-conditioned eye. Test stimulation periods were alternated with 1 min conditioning periods in order to minimize shrinkage of the expanded receptive field by direct visual stimulation.

The cell population studied included complex cells in the superficial layers of the adult cat visual cortex. Complex cells were defined according to the criteria of Hubel and Wiesel (1962). Since penetrations were made into the dorsal surface of the lateral gyrus, were limited to a depth of 500 μm, and cells had receptive field properties characteristic of superficial layer cells (Gilbert, 1977), we were confident of the laminar location.

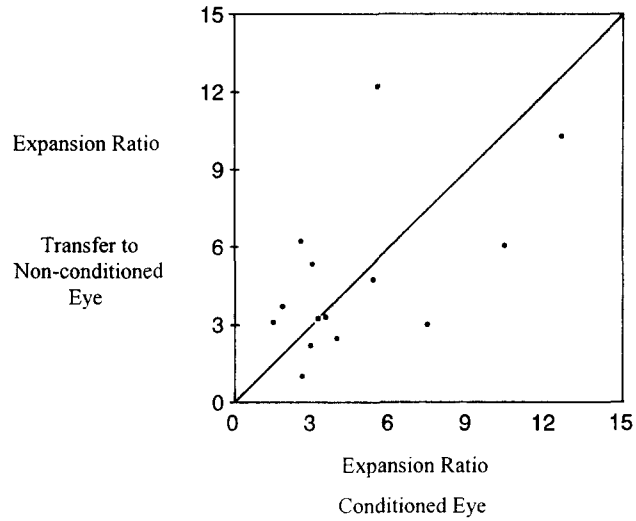

FIGURE 2. Comparison of the extent of expansion of the receptive field in the conditioned eye with that in the non-conditioned eye. The ratio of expansion was calculated as the receptive field area measured during conditioning divided by the area measured before conditioning. This ratio was determined for both the field in the conditioned and non-conditioned eye, and the scatter plot shows the compared ratios for 11 cells and three multi-unit recordings. Expansion in the conditioned eye was associated with expansion in the non-conditioned eye, and larger expansions in one correlated with larger expansions in the other.

RESULTS

Of the 12 single cells, we observed interocular transfer of the receptive field expansion in 11. Interocular transfer was also seen in three out of the four multi-unit recordings. For seven of the single unit recordings the expansion was quantified by the computerized visual stimulator/data acquisition systems. Response histograms for the different test bar positions were obtained for the non-conditioned eye before conditioning of the other eye, during the conditioning period, and after stimulation of the receptive field center in the initially conditioned eye. The quantitative tests confirmed the results obtained from hand-held stimulation that the receptive field in the non-conditioned eye expanded during the period of conditioning of the other eye, and that the effect was reversed by stimulating within the receptive field center of the conditioned eye.

Figure 1 shows examples of receptive field maps for the two eyes plotted for each eye prior to and subsequent to conditioning of one eye. In each of the examples there was a clear expansion in the receptive field of the non-conditioned eye, roughly of the same magnitude as that observed for the conditioned eye. The ratio of the expanded over the contracted receptive field areas was calculated for each eye, and compared in Fig. 2. The figure shows this comparison for conditioned vs non-conditioned eye for 14 out of the 16 single and multi-unit maps, with the points falling approximately along a line of equal expansion in the two eyes (diagonal line in the graph of Fig. 2). The receptive field areas in the conditioned eye increased by an average ratio of 4.6 ($\pm$3.1), and in the non-conditioned eye by a ratio of 4.8 ($\pm$3.3).

The results of the response histograms showing the quantitative comparisons of pre- and post-conditioning receptive fields are shown in Fig. 3(a, b). The histograms indicate the integrated activity for a sweep of a test bar positioned at different positions along the orientation axis of the cell, presented to the non-conditioned eye. The cross hatched bars represent the activity of the cell before conditioning one eye with the artificial scotoma, and the diagonally hatched bars during conditioning. The figure shows the response to stimulation of the non-conditioned eye before and during conditioning of the other eye. The number of spikes per sweep increased for stimuli moving across the original receptive field as well as outside its original limits, as was shown previously by Pettet and Gilbert (1992) for the conditioned eye. These figures emphasize the expansion along the orientation axis of the cell, but as shown by both the hand mapping and by the individual response histograms for each position of the test bar, we found expansion along the orthogonal axis as well. The hand maps (shown below the histograms) agree with the maps obtained by quantitative mapping.

DISCUSSION

We conclude that alteration of the receptive field boundaries occurring in response to stimulation with an artificial scotoma shows interocular transfer. This finding suggests that the circuits involved in the dynamic alteration of receptive field size are localized within the cortex. Because of the interocular transfer, it is most plausible to assume that the cells responsible for the change in receptive field size are binocular, and binocular cells are first found in the striate cortex. It is conceivable that a monocular input converging onto a binocular cortical cell, mediated by geniculate afferents, can alter the responsiveness of the cortical cell to inputs from the other eye, and this possibility can be tested by recording from simple cells in layer 4. But the magnitude

of the expansion can be best explained by the binocular, pyramidal cells in the superficial layers that extend long range horizontal connections (Gilbert & Wiesel, 1979, 1983; Martin & Whitteridge, 1984). Their axons travel over distances up to 6–8 mm within area 17, allowing the target neurons to integrate information from outside the scotoma. Another potential source of long range projections is the feedback projection from higher order cortical areas (Perkel, Bullier & Kennedy, 1986; Rockland & Virga, 1989; Salin, Girard, Kennedy & Bullier, 1992). It is likely that the expansion involves an increase in synaptic weight, though there are several mechanisms through which this can be brought about, including potentiation of excitatory connections [as has been demonstrated for the horizontal connections in cortical slices (Hirsch & Gilbert, 1993)] or by adaptation of inhibitory connections. The finding of interocular transfer is not an artifact of occlusion of the non-conditioned eye, since we have shown previously that eye occlusion or dark adaptation does not by itself cause receptive field expansion, but rather requires the active conditioning of the extended receptive field surround (Pettet & Gilbert, 1992, Fig. 4).

The fact that interocular transfer can be observed after a few minutes of conditioning raises the possibility that the longer term effects caused by retinal lesions might be produced by monocular lesions, and might transfer to the non-lesioned eye. One report of an interocular effect of retinal lesions was reported by Craik (1966), who made a self-induced foveal, monocular lesion by staring at the sun with one eye while shielding the other eye. He reported that lines falling on the lesioned part of the affected retina appeared to be constricted over that area, and that lines in the other eye appeared to be widened in their course over the homologous region. Although we do not know to what extent the changes observed with artificial scotomata can be compared with the effects of laser-induced scotomata, our results would also suggest that monocular retinal lesions could induce changes at the topographically appropriate cortical regions serving both eyes, not just the fields from the lesioned eye.

The demonstration of interocular transfer is not only a useful tool for determining the site(s) along the visual pathway that may be responsible for the receptive field expansion, but also provides a point of comparison with psychophysical studies attempting to determine the role of receptive field expansion in perception. For example, certain learning effects have been shown to have the characteristics of early vision (Butler & Westheimer, 1978; McKee & Westheimer, 1978; Badcock & Westheimer, 1985; Karni & Sagi, 1991; Poggio, Fahle & Edelman, 1992; Kapadia, Gilbert & Westheimer, 1995), but in general these effects do not show interocular transfer. There are a number of unresolved issues concerning the site of learning, however: the lack of

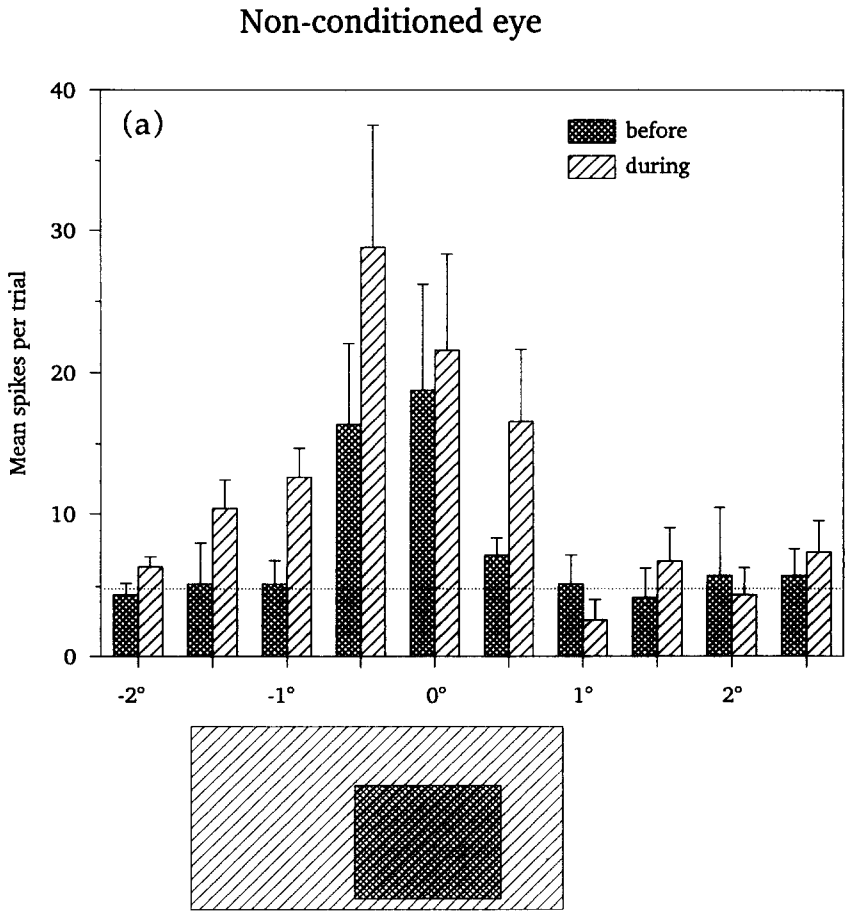

FIGURE 3(a). *Caption on facing page.*

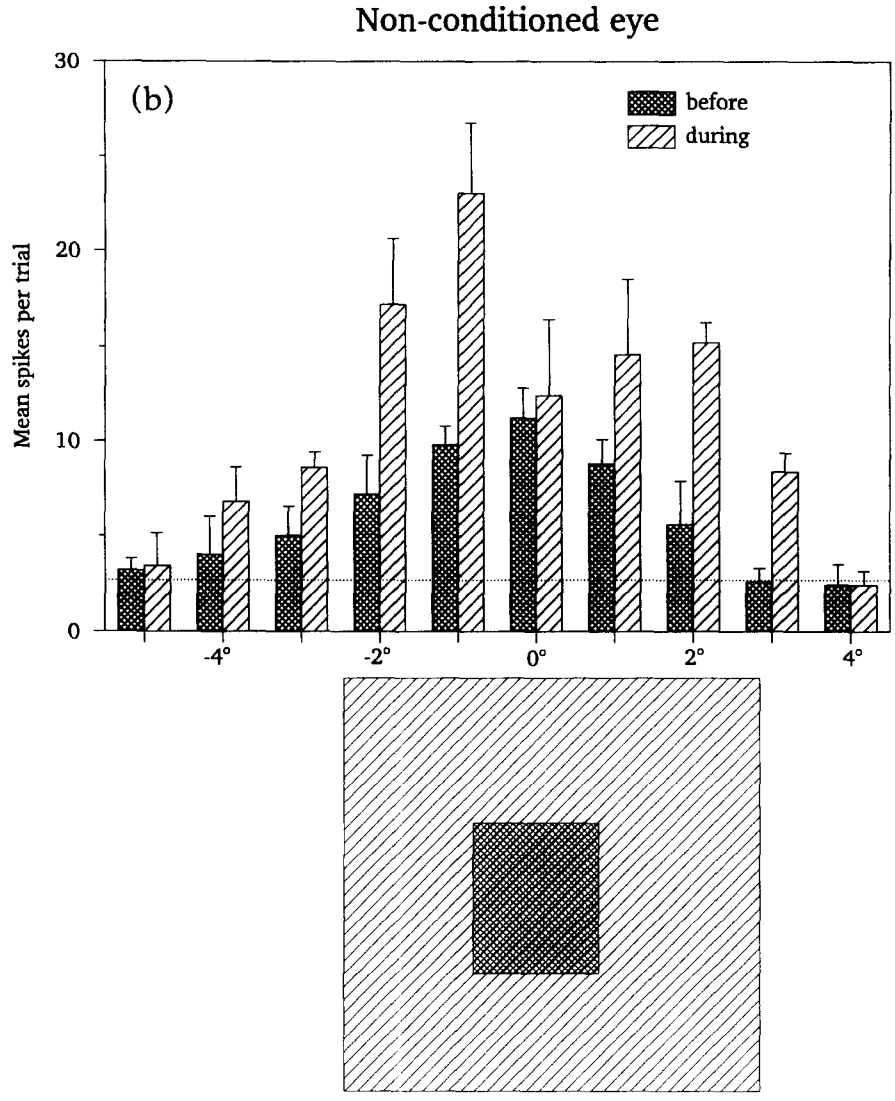

FIGURE 3. Quantitative mapping of receptive fields before and during artificial scotoma-induced expansion, for two of the single units studied. Test bars, $\frac{1}{8}$ deg × $\frac{1}{2}$ deg, were placed at different positions along the orientation axis of the cell, and swept back and forth in the orthogonal direction. During conditioning the test bar presentations were interdigitated with conditioning stimuli in order to avoid collapsing the receptive field by moving stimuli through the field. Five trials were taken for each stimulus position. The response histograms were integrated to give a value of spikes/sweep. The histogram bars reflecting activity before conditioning are shaded with cross-hatching, and those indicating activity during conditioning filled with diagonal lines. The level of spontaneous activity for each cell is indicated by the horizontal dotted line spanning the histogram. Below each histogram are two-dimensional maps of the receptive field obtained by hand mapping, which agrees well with the quantitative mapping. (a) and (b) show the results for two superficial layer complex cells in cat area 17. The error bars indicate SEM for each bar position.

interocular transfer and orientation specificity is taken as evidence for involvement of early visual processing, particularly V1, but by and large oriented cells are binocular as well, and may not be expected to show eye-specific effects.

REFERENCES

Badcock, D. R. & Westheimer, G. (1985). Spatial location and hyperacuity: The centre–surround localization function has two substrates. *Vision Research, 25*, 1259–1269.

Butler, T. & Westheimer, G. (1978). Interference with stereoscopic acuity: Spatial, temporal, and disparity tuning. *Vision Research, 18*, 1387–1392.

Chino, Y. M., Kaas, J. H., Smith, E. L III, Langston, A. L. & Cheng, H. (1992). Rapid reorganization of cortical maps in adult cats following restricted deafferentation in retina. *Vision Research, 32*, 789–796.

Craik, K. J. W. (1966). *The nature of psychology* (Chaps 9 and 10). Cambridge: Cambridge University Press.

Gilbert, C. D. (1977). Laminar differences in receptive field properties of cells in cat primary visual cortex. *Journal of Physiology, 268*, 381–421.

Gilbert, C. D. & Wiesel, T. N. (1979). Morphology and intracortical projections of functionally identified neurons in cat visual cortex. *Nature, 280*, 120–125.

Gilbert, C. D. & Wiesel, T. N. (1983). Clustered intrinsic connections in cat visual cortex. *Journal of Neuroscience, 3*, 1116–1133.

Gilbert, C. D. & Wiesel, T. N. (1990). The influence of contextual stimuli on the orientation selectivity of cells in primary visual cortex of the cat. *Vision Research, 30*, 1689–1701.

Gilbert, C. D. & Wiesel, T. N. (1992). Receptive field dynamics in adult primary visual cortex. *Nature, 356*, 150–152.

Heinen, S. J. & Skavenski, A. A. (1991). Recovery of visual responses in foveal V1 neurons following bilateral foveal lesions in adult monkey. *Experimental Brain Research, 83*, 670–674.

Hirsch, J. & Gilbert C. D. (1993). Long-term changes in synaptic strength along specific intrinsic pathways in the cat's visual cortex. *Journal of Physiology, 461*, 247–262.

Hubel, D. H. & Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *Journal of Physiology, 160*, 106–154.

Kaas, J. H., Krubitzer, L. A., Chino, Y. M., Langston, A. L., Polley, E. H. & Blair, N. (1990). Reorganization of retinotopic cortical maps in adult mammals after lesions of the retina. *Science, 248*, 229–231.

Kapadia, M., Gilbert, C. D. & Westheimer, G. (1995). A quantitative measure for short-term cortical plasticity in human vision. *Journal of Neuroscience*. In press.

Karni, A. & Sagi D. (1991). Where practice makes perfect in texture discrimination: Evidence for primary visual cortex plasticity. *Proceedings of the National Academy of Science, U.S.A., 88*, 4966–4970.

Martin, K. A. C. & Whitteridge, D. (1984). Form, function and intracortical projections of spiny neurones in the striate visual cortex of the cat. *Journal of Physiology, 353*, 463–504.

McKee, S. P. & Westheimer, G. (1978). Stereoscopic acuity for moving retinal images. *Journal of the Optical Society of America, 68*, 450–455.

Perkel, D. J, Bullier, J. & Kennedy, H. (1986). Topography of the afferent connectivity of area 17 in the macaque monkey: A double-labelling study. *Journal of Comparative Neurology, 253*, 374–402.

Pettet, M. W. & Gilbert, C. D. (1992). Dynamic changes in receptive field size in cat primary visual cortex. *Proceedings of the National Academy of Science, U.S.A., 89*, 8366–8370.

Poggio, T., Fahle, M. & Edelman, S. (1992). Fast perceptual learning in visual hyperacuity. *Science, 256*, 1018–1021.

Rockland, K. S. & Virga, A. (1989). Terminal arbors of individual "feedback" axons projecting from area V2 to V1 in the macaque monkey: A study using immunohistochemistry of anterogradely transported phaseolus vulgaris-leucoagglutinin. *Journal of Comparative Neurology, 285*, 54–72.

Salin, P. A., Girard, P., Kennedy, H. & Bullier, J. (1992). Visuotopic organization of corticocortical connections in the visual system of the cat. *Journal of Comparative Neurology, 320*, 415–434.

Acknowledgements—The work was supported by grant CNPq 202806-91.0 and NSF grant INT9001695 (E.V.); and NIH grant EY07968 and a McKnight Foundation development award (C.G.). We thank Ella Lears for technical assistance.